Individually-addressed planar nanoscale InGaN-based light emitters

D. Massoubre[1], P. R. Edwards[2], E. Xie[1], E. Richardson[1], I. M. Watson[1], E. Gu[1],
R. W. Martin[2] and M. D. Dawson[1].

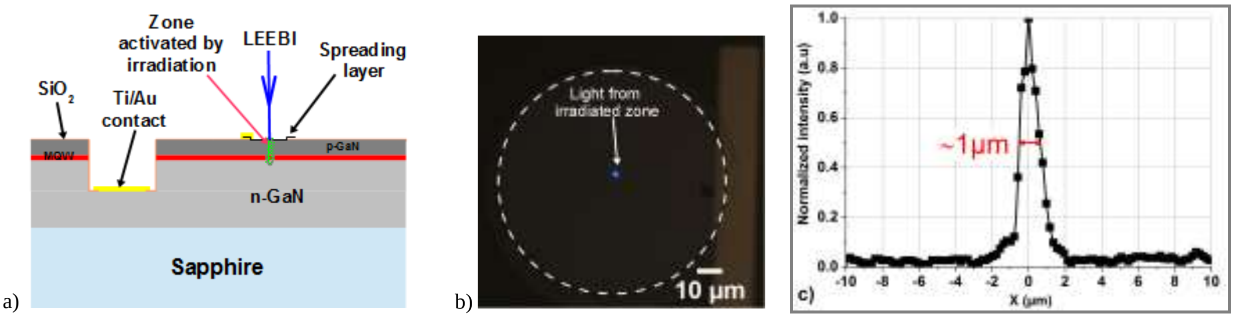
[1]*Institute of Photonics, SUPA, University of Strathclyde, Glasgow, Scotland, UK, G4 0NW*
[2]*Department of Physics, SUPA, University of Strathclyde, Glasgow, Scotland, UK, G4 0NG*

Email addresses: david.massoubre@strath.ac.uk

Abstract: We report on a new fabrication approach to create individually-addressable InGaN-based nanoscale-LEDs. It is based on the creation by LEEBI of a spatially confined sub-micron-size charge injection path within the p-GaN of an LED structure.

Introduction: The development of nano-scale InGaN-based light emitting diodes (LEDs) has attracted much interest in recent years, mainly as a nano-structuring of broad-area devices to improve their efficiency for lighting applications [1]. Besides the scientific interest in the studies of such small structures, nano-sized light emitters are, however, also of strong interest for areas including nano-lithography and nano-scale direct writing, efficient resonant energy transfer to molecular and quantum dot materials, and in various applications in bioscience. Two basic approaches have been developed to fabricate interconnected nano-LED arrays, respectively involving 'top-down' dry etching of nano-rod structures, and 'bottom-up' advanced epitaxial growth [2]. These approaches have their respective advantages, but both have the disadvantage of requiring complex device processing due to the 3D nature of the nano-rod-shaped LEDs. Furthermore etch-based fabrication routes induce damage on mesa sidewalls that may dominate the characteristics of sub-micron devices [3]. Consequently, while electrically-pumped interconnected nano-LEDs have already been fabricated, the only few reports of singly-addressed nano-rod-based LEDs were achieved thanks to the use of external nano-probes which are not suitable for applications and further characterization [4].

In order to overcome these difficulties, we are working on a new route for the fabrication of InGaN-based nanoscale light emitters. Our approach is based on the creation of spatially confined carrier injection paths within the p-doped GaN layer of a 'standard' LED structure. The modulation of the p-GaN conductivity is achieved here by activating the Mg-doping of a top GaN layer with low-energy electron beam irradiation (LEEBI). This technique harks back to early work in activating p-dopant in broad area GaN LEDs but when, as here, the activation is localized via a nanoscale focussed electron beam, we can create laterally confined carrier injection paths through the Mg-doped top GaN layer. This leads to the light emission from the underlying quantum wells having a spot size mainly limited by the irradiated area. Robust individually-addressed monolithic light emitters at around 1μm in size have successfully been created by this approach, with sub-micron operation in prospect.



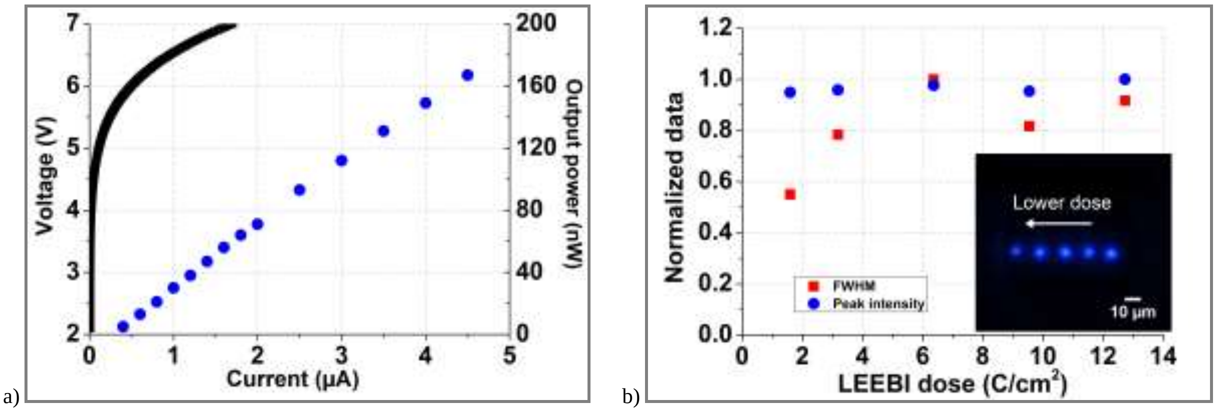
Figs. 1 – (a) Schematic of the device design showing the local LEEBI activation principle. Light emission and its intensity profile from a LEEBI-induced emitter are shown respectively in (b) and (c). The dashed white line on (b) shows the limit of the SiO_2 aperture.

Design and fabrication of the device: A standard commercial non-activated p-i-n LED wafer, grown on c-plane sapphire and with peak emission wavelengths at 450 nm was used. A schematic of the design of the device used in this study is shown in Fig. 1.a. A patterned photoresist mask was used to create a trench down to the n-doped GaN layer by inductively coupled plasma dry etching. This trench serves as a shared negative electrode for our nanoscale LEDs. A 300 nm-thick SiO_2 layer was deposited by plasma-enhanced chemical vapor deposition (PECVD). Apertures to access the p-doped GaN surfaces and the bottom of the trench were then created in the SiO_2 layer by lithography and reactive ion etching. The apertures on top of the p-GaN layer have diameters of 96 μm and 80 μm, respectively, and are used to delimit the area where each nanoscale LED is created. It should be noted that the whole process could be applied with different aperture sizes as, so far, no effect from this parameter on the light emitter size has been detected. The sample was next soaked in an HCl solution to remove the native oxide, immediately followed by the deposition of a semi-transparent metal layer over the SiO_2

aperture using electron beam evaporation. This thin metal layer acts as a current-spreading layer. Tracks, n-pads and p-pads consisting of a 50 nm/200 nm Ti/Au bilayer were also deposited by sputtering and patterned by a lift-off process. Finally, a localized LEEBI was used to create the light emitters as shown in Fig. 1.a. For this initial investigation, the LEEBI was carried using a 10 keV e-beam from a Cameca SX100 electron probe microanalyser. For characterization purposes, the device was finally wire-bonded onto a printed circuit board.

Experimental results and discussion: Fig. 1.b shows an image of a light emitter created by LEEBI in this way, and the intensity profile extracted from this image is shown in Fig. 1.c. This emitter was created using a 2 nA e-beam current, an exposure time of 60 s and a sub-micron beam spot (the spot size in this case being limited by the e-beam focus), leading to a minimum electron dose of 15 C/cm^2. As expected, we see that the light emission is well confined within the LEEBI zone without any unwanted light from any non-irradiated areas. Furthermore, the output light is clearly visible to the naked eye, demonstrating a relatively high output power. We believe that the LEEBI enables activation of acceptors by dissociating the MgH complex in the as-grown Mg-doped GaN layer leading to a preferential hole injection path [5]. As the thickness of the p-GaN layer (<150 nm) is larger than the carrier lateral diffusion length in GaN [6], the electrons and holes recombine in the active zone below this conduction channel, leading to strongly localised light emission. The absence of parasitic light emission and the robustness of the LEEBI-induced light emitter enable standard electrical and optical measurements to be performed. As shown in Fig. 2.a, the nanoscale light emitter shows diode behaviour with a turn-on voltage around 5 V, which is only slightly higher than that of a standard broad-area LED. The absence of leakage current (combined with no unwanted light emission) demonstrates that most of the current is indeed efficiently confined in the LEEBI-induced current injection path. The output power, also plotted in Fig. 2.a, shows an approximately linear increase with the injection current. By taking an emitter spot radius of 500 nm (taken from the half width half maximum of the intensity profile in Fig. 1.c), an average top-emitted output power density of 22 W/cm^2 at 4.5 µA is obtained.

The effect of the LEEBI dose was also investigated by creating five 15-µm-pitch emitters in the same SiO_2 aperture as shown in the inset in Fig. 2.b. The LEEBI dose was changed for each emitter by reducing the exposure time from 40 s down to 5 s, with a constant beam current of 10 nA and a spot size of 2 µm (achieved by controlling the beam defocus). The relative FWHM and peak intensity for each emitter were deduced from the image shown in inset in Fig. 2.b and are plotted in Fig. 2.b. Experimental results show a factor of 2 reduction of the FWHM when the dose is reduced from 13 C/cm^2 down to 1.6 C/cm^2. As we do not expect any change in the lateral dose profile at fixed e-beam energy, this reduction could be explained by a decrease of the zone (at lower exposure time) receiving a dose above the necessary threshold for activation. Fig. 2.b also shows that the peak output intensity does not significantly change over the investigated dose range, meaning that the efficiency is kept constant even if the emitter size is reduced. These initial results, performed at a LEEBI dose lower than for the emitter shown on Fig. 1.b, show that there is still room to significantly decrease the light emitter size by optimising the LEEBI parameters.



a) b)

Figs. 2 – (a) I-V and L-I curves from a ~1µm-diameter LEEBI-induced InGaN LED. (b) Normalized FWHM and peak intensity versus the LEEBI dose, deduced from the image shown on the inset.

Conclusions: In summary, we demonstrate a new fabrication approach to create nanoscale-size GaN-based LEDs from planar LED structures, which consists of laterally confining the charge carriers in a preferential injection path. The injection path is created by modulating the p-GaN conductivity using the LEEBI technique. Individually-addressable GaN-based nanoscale-size LED were successfully fabricated and characterized.

References:

[1] A. Waag *et al.*, phys. status sol. (c) **8**, 2296 (2011).
[2] S. Li *et al.*, J. Appl. Phys. **111**, 071101 (2012).
[3] L. Chen *et al.*, phys. stat. sol. (a) **188**, 135 (2001)
[4] S. D. Hersee *et al*., Electron. Lett. **45**, 75 (2009).
[5] H. Amano *et al.*, Jpn. J. Appl. Phys., **28**, L2112 (1989).
[6] J. Danhof *et al.*, Phys. Rev. B, **84** , 035324 (2011).